M. R. Oliver (Ed.)

Chemical-Mechanical Planarization of Semiconductor Materials

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6 CMP Polishing Pads

David B. James

6.1 Introduction

Although polishing is an old technology [1, 2, 3], it has become an enabling process for the manufacture of leading-edge semiconductor devices. In the manufacture of such devices, polishing is used to maintain planarity at each step in the process of depositing and photolithographically imaging sequential insulating dielectric and conductive metal layers. Also as noted in the first chapter, CMP is now also employed to remove a bulk film and then stop, as in damascene copper and tungsten polishing. As semiconductor devices become increasingly complex, requiring finer feature geometries and more metallization layers, greater demands are placed on the polishing consumables used in the CMP process to manufacture such devices [4, 5, 6].

Polishing consumables usually comprise a polymeric polishing pad used in conjunction with an aqueous based polishing slurry [7]. Conventionally, the slurry contains abrasive particles but, also recently, two variants on the standard consumables have been studied. In the first new approach, the abrasive particles have been incorporated into the pad and in the second, the pad is used with a particle-free reactive liquid. This chapter will focus on conventional polishing pads and, for completeness, will include only a brief section on slurryless pad technology. More specifically, this chapter will discuss polymer criteria for polishing pads, types of pads available and their manufacture, control of pad properties, and the relationship of those properties to polishing performance.

6.2 Polymer Requirements for Polishing Pads

Since polishing is both a mechanical and a chemical process, the polymeric polishing pad must have sufficient mechanical integrity and chemical resistance to survive the rigors of polishing. As discussed later in this chapter, important mechanical properties include high strength to resist tearing during polishing, acceptable levels of hardness and modulus selected based on the material being polished, and good abrasion resistance to prevent excessive

168   David B. James

Chemically, the pad must be able to survive the aggressive slurry chemistries used in CMP polishing without degrading, delaminating, blistering or warping. Slurry chemistries include either highly alkaline slurries near pH 11 used for polishing of inter-layer dielectric oxide layers or highly acidic, oxidizing slurries used for polishing metal films, such as tungsten and copper. Slurries for metal CMP can have pH values less than 2 and contain oxidizing agents such as hydrogen peroxide, ferric nitrate or potassium iodate. Typically, over the lifetime of a single pad, it is exposed to these chemistries for many hours and often several days, usually at temperatures above ambient.

A third criterion is that the pads must be sufficiently hydrophilic. The aqueous-based abrasive containing slurry or the particle-free reactive liquid must wet the surface of the pad and form a liquid film between the wafer and the pad. If the liquid does not wet but instead beads on the pad surface, it will be swept away by the wafer edge and the interior of the wafer will be starved of the necessary chemistry to enable effective polishing.

Pad hydrophilicity may be expressed in terms of the pad's Critical Surface Tension. This is defined as the wettability of a solid surface by noting the lowest surface tension a liquid can have and still exhibit a contact angle greater than zero degrees on that solid. In terms of polishing, this means that pads made from polymers with higher critical surface tension values are more hydrophilic and slurry will more readily wet these pads.

Table 6.1 shows critical surface tension values for several commercially available polymers [8].

From the Table 6.1, polymers with higher critical surface tension values correspond to those polymers which are useful as polishing pads. The minimum value is around 37 mN/m, and preferred values are in the mid 40's. This range includes polymers such as poly(methyl methacrylate), polycarbonates, nylons, polysulfones, and polyurethanes.

As the critical surface tension of the pad decreases, polishing performance will also decrease. Thus one would expect polyethylene and PTFE pads to perform poorly because slurry does not spread over the pad surface. However, a number of approaches have been used to enable less hydrophilic polymers to be used as polishing pads. These include adding high levels of wetting agents to the slurry, adding hydrophilic fillers such as silica to normally hydrophobic polymers, or by chemically modifying the hydrophobic polymer to make it more hydrophilic. Techniques used for the latter include plasma treatment, corona discharge or the chemical addition of polar groups to the pad surface. However, since pads are continually abraded during use, either by conditioning prior to polishing or by the polishing process itself, the treatment needs to be effective through the whole cross-section of the pad and not just the surface layer.

Since polishing is a wet process, the mechanical properties of the pad must be essentially retained, even when the pad is wet. However, the properties

Table 6.1. Critical Surface Tension Values of Polymers

Polymer	Critical Surface Tension (mN/m)
Polytetrafluoroethylene	19
Polydimethylsiloxane	24
Silicone Rubber	24
Polybutadiene	31
Polyethylene	31
Polystyrene	33
Polypropylene	34
Polyacrylamide	35 – 40
Polyvinyl alcohol	37
Polymethyl methacrylate	39
Polyvinyl chloride	39
Polysulfone	41
Nylon 6	42
Polycarbonate	45
Polyurethane	45

during exposure to aqueous polishing slurries. Typically water acts as a plasticizer which decreases pad modulus and hardness, and increases ductility. Thus under polishing conditions, the pads will become more ductile and flexible. These changes are reversible and pad properties revert to the original values on drying, indicating that chemical attack of the pad is minimal.

The changes in pad properties during polishing are important for those researchers interested in modeling the mechanisms of CMP polishing. Often dry properties rather than the more appropriate wet properties are used in the models. Secondly, most properties measured are bulk properties. Since polishing is an interfacial process, in many cases the properties of the pad surface rather than the bulk should be used. Surface properties change rapidly during immersion in slurry and quickly reach equilibrium values [61].

The final criterion for the polymer is that the polymer formulation and morphology can be varied to give pads with specific, predictable properties for different polishing applications. Thus a family of pads is preferred, such that performance may be fine-tuned for the specific polishing application, polishing tool, wafers and slurry.

The types of polymers which best satisfy the criteria discussed above are polyurethanes. Polyurethanes combine good mechanical properties with excellent chemical stability and, as shown in the next section, their proper-

170   David B. James

technology it is possible to fabricate a wide range of pad microstructures including foams, impregnated felts and solid pads, and to use a variety of polyurethane manufacturing processes including casting, molding, extrusion, web-coating and sintering. These will be discussed in more detail later in the chapter.

6.3 Basics of Polyurethanes

Many books have been written covering the chemistry, morphology, properties and manufacture of polyurethanes, and the reader is referred to these [9, 10, 11] for in-depth discussions. This section will provide a brief overview of polyurethanes and cover those aspects most relevant to polishing pad technology.

6.3.1 Formulations

Polyurethanes are typically composed of at least three components:

1. Long chain polyol
2. Diiocyanate or isocyanate of higher functionality
3. Chain Extender.

Most polyols used in the manufacture of polyurethanes are polyethers with terminal hydroxyl groups. Hydroxyl-terminated polyesters are sometimes used to obtain polyurethanes with special properties. However, polyester diols tend to be more expensive and are less chemically stable than polyether diols, especially in basic solution. The choice of polyol, especially the size (molecular weight), flexibility of its molecular structure, and functionality, has a large effect on the properties of the resultant polyurethane.

A second method of varying the properties of a polyurethane is through the selection of the isocyanate. Several aromatic and aliphatic isocyanates are available, but 95% of all polyurethanes are based on either toluene diisocyanate (TDI) or diisocyanato-diphenylmethane (MDI) and its derivatives. MDI is often preferred over TDI because of its lower toxicity and greater chemical flexibility. Although pure MDI is a difunctional solid having two reactive isocyanate groups per molecule, producers of isocyanates have developed liquid MDI variants of higher functionality than two. This enables control of crosslinking reactions and hence of the resultant polyurethane properties.

The third important component in a polyurethane formulation are small molecules known as chain extenders. These are chemicals containing groups which can react with isocyanates and link such isocyanates together to introduce specialized polymer segments into the polyurethane backbone. Ex-

Fundamentally, there are three approaches to formulating polyurethanes, described by the urethane industry as "prepolymer", "quasi", and "one-shot". In the "one-shot" approach all the components are mixed together and reacted at one time. This can result in a highly exothermic reaction which is more difficult to control and can lead to reproducibility problems. In the "prepolymer" approach, the isocyanate is pre-reacted with the long chain diol to form a high molecular weight isocyanate terminated moiety. This can then be further reacted with diol or diamine curatives to complete the polyurethane formation. The advantages of this approach are greater control over the chemistry and a more consistent product. The "quasi" approach is intermediate between the two other approaches.
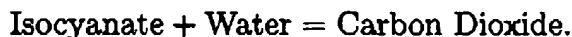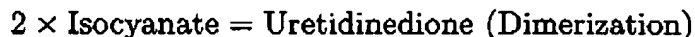
Additional ingredients commonly included in commercial polyurethane formulations for polishing pads are catalysts, fillers and blowing agents.

6.3.2 Chemistry

Polyurethanes are addition polymers [12] formed by reaction of di- or polyfunctional isocyanates with polyols:

$$\text{Polyol} + \text{Isocyanate} = \text{Polyurethane.}$$

However, urethane reactions are actually much more complex. This is a consequence of the high reactivity of isocyanates which can react with any molecules present containing active hydrogen groups, and by the fact that it is usual to use a stoichiometric excess of isocyanate with respect to diol. Thus, under suitable conditions, many secondary reactions are possible, such as:

$$\text{Isocyanate} + \text{Urethane} = \text{Allophanate}$$

$$2 \times \text{Isocyanate} = \text{Uretidinedione (Dimerization)}$$

$$3 \times \text{Isocyanate} = \text{Isocyanurate (Trimerization)}$$

$$\text{Isocyanate} + \text{Water} = \text{Carbon Dioxide.}$$

These reactions can be preferentially controlled through the reaction conditions. Thus one reaction over another can be favored through the use of catalysts and by controlling the reaction temperature. The first three of the above reactions create chemical cross-links between chains and a network structure. As will be illustrated later, as a consequence of the polyurethane cross-linking reactions, pad properties can be fine-tuned through control of the stoichiometric ratio of isocyanate to diol.

6.3.3 Morphology

172   David B. James

ear, highly extensible elastomers. A common feature, however, of polyur-
ethanes is the presence of so-called "soft" and "hard" segments. The type
and relative amount of these in the polyurethane structure are major deter-
minants in controlling polyurethane properties.

Soft segments are quite mobile and are normally present in coiled forma-
tion. Chemically, they comprise the high molecular weight long chain diol
component of the formulation. The mobility of molecular chains in the soft
segment results in increased flexibility, toughness and impact resistance. Mo-
bility depends on the chemical nature and chain length of the soft segment.
Ideally, the soft segment should be amorphous and have a low glass tran-
sition temperature. Phase separation increases with increasing chain length
and decreasing polarity of the soft segment due to less hard segment/soft
segment interaction. Preferred molecular weights are in the 1000 to 4000
range. At higher molecular weights, especially at low hard segment amounts,
there is a tendency for the soft segments to crystallize which will reduce the
elastomeric benefits conferred by the soft segments.

Soft segments alternate with hard segments which are stiff oliourethane
units, principally composed of reacted isocyanate and chain extender moi-
eties. Hard segments act as pseudo cross-links and control the dimensional
thermal stability of polyurethanes. Thus properties such as strength and stiff-
ness at elevated temperatures are controlled by the hard segments. Above
a certain temperature, the hard segments "melt" and, in the absence of
chemical cross-links, the polyurethane becomes thermoplastic with greatly
reduced strength and stiffness.

6.4 Types of Commercially Available Polishing Pads and Their Manufacture

6.4.1 Types of Pads

This section will cover the types of pad that are commercially available and
currently used for CMP polishing. Following the classification of Cook [13],
the pads may be categorized into four types differentiated by their microstruc-
ture. The types are:

Type 1: Polymer Impregnated Felts
Type 2: Poromerics (synthetic leathers)
Type 3: Filled Polymer Sheets
Type 4: Unfilled Textured Polymer Sheets.

Table 6.2 summarizes the key features, properties, commercial trade
names, and typical applications for the different pad types.

Table 6.2. Key Features, Properties and Applications for Different Pad Types

	Type 1	Type 2	Type 3	Type 4
Structure	Felted fibers impregnated with polymeric binder	Porous film coated on a supporting substrate	Microporous polymer sheet	Non-porous polymer sheet with surface macrotexture
Microstructure	Continuous channels between fibers	Vertically oriented, open pores	Closed cell foam	None
Slurry loading capacity	Medium	High	Low	Minimal
Pad Examples	Pellon^{TM}, Suba^{TM}	Politex^{TM}, Surfin^{TM}, UR100^{TM}, WWP3000^{TM}	IC1000^{TM}, IC1010^{TM}, IC1400^{TM}, FX9^{TM}, MH^{TM}	OXP3000^{TM}, IC2000^{TM}
Compressibility	Medium	High	Low	Very Low
Stiffness	Medium	Low	High	Very High
Hardness	Medium	Low	High	Very High
Typical Applications	Si stock polish, Tungsten CMP	Si final polish, Tungsten CMP, post-CMP buff	Si stock, ILD CMP, STI, metal damascene CMP	ILD CMP, STI, metal dual damascene
Key Patents	US 4,728,552 4,927,432	3,100,721 3,763,054 4,841,680 6,099,954	5,578,362 5,900,164	5,489,233 6,022,268

Note: Suba^{TM}, Politex^{TM}, UR100^{TM}, WWP3000^{TM}, IC1000^{TM}, IC1010^{TM}, IC1400^{TM}, MH^{TM}, OXP3000^{TM}, and IC2000^{TM} are trade-names of Rodel Inc., Pellon^{TM} and FX9^{TM} of Freudenburg, and Surfin^{TM} of Fujimi.

6.4.2 Methods of Manufacture

Although all the four pad types are polyurethane based, each is manufactured by a different process, illustrating the versatility of urethane chemistry. Table 6.3 provides a schematic outline of the manufacturing process for the different pad types. Types 1 and 2 pads are manufactured by a continuous roll or web process, Type 3 pads by a batch process, and Type 4 pads by either a batch process or by a unit operation, net shape process. Emerging, alternative manufacturing processes will be discussed later in this section.

Each manufacturing process has its own advantages and limitations, and

174   David B. James

Table 6.3. Manufacturing Processes for Different Pad Types

Type 1	Type 2	Type 3	Type 4
Needle polyester fibers to form non-woven felt	Prepare supporting substrate using modified Type 1 process	Mix polyurethane precursors and pore forming agent	Form polymer sheet
1st Urethane Impregnation	Coat substrate with polyurethane solution	Cast into mold	Apply texture (e.g. grooves)
2nd Urethane Impregnation	Coagulate surface film	Cure at elevated temperature	Apply PSA
Split Impregnated Felt to required thickness	Buff to open pore structure and control thickness	Skive cake into individual pad slices	Laminate to Base Pad
Buff	Apply PSA	Perforate or groove	
Apply PSA		Apply PSA	
		Laminate to Base Pad	

process variables which can be used to control pad properties. The effects of manufacturing process variables on pad properties have been recently discussed by Cook [13] and the reader is referred to this reference for more information.

Currently, Type 3 pads, because of their higher stiffness and resultant ability to planarize versus Type 1 and 2 pads, are predominantly used for CMP polishing of ILD, W, Cu and STI. It is expected that Type 4 pads may emerge as the next generation pad of choice because of their potentially less complex manufacturing process, resulting in improved pad to pad consistency and more predictable polishing performance. Data illustrating the benefits of Type 4 pads will be discussed in more depth later.

The patent literature describes several novel approaches to manufacture pads for CMP polishing. The principal driving forces are to:

1. Simplify manufacturing processes to ensure increased pad to pad consistency
2. Eliminate skiving and machine grooving operation
3. Develop net shape manufacturing process capable of producing patterned polishing pads having a wide range of physical properties
4. Develop processes capable of linear pads for next generation polishers

Table 6.4. US Patents describing Alternative Manufacturing Processes

Manufacturing Approach	US Patents
Sintering of Polymeric Powders	6,017,265, 6,062,968, 6,106,754, 6,117,000, 6,126,532
Photopolymerization of Liquid Precursors	5,958,794, 6,036,579
Net-shape Molding	6,022,268
Extrusion of thermo-formable polymers	5,489,233, 6,022,268

Each of these approaches has strengths and weaknesses. The preferred process depends both on the type of material being polished and on the tool platform.

6.4.3 Pad Microstructures

Each type of pad has a unique microstructure, as shown in the following SEM photomicrographs. Commercially available polishing pads are composite materials with properties determined by both their microstructure and polyurethane formulation.

Figures 6.1 and 6.2 show the cross-section and surface microstructures respectively of a Type 1 pad, as exemplified by Suba 500™. The microstructure is characterized by non-woven polyester fibers, partially impregnated with polyurethane to leave open porosity throughout the pad. By controlling
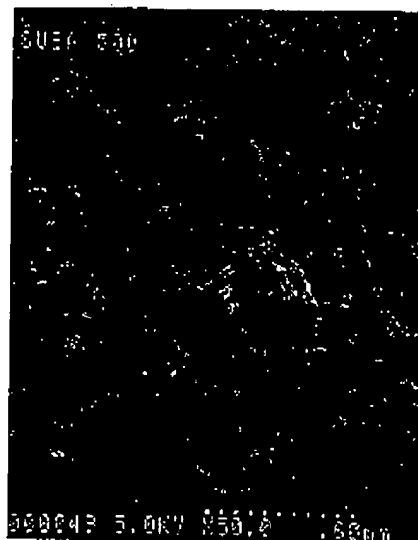
176 David B. James
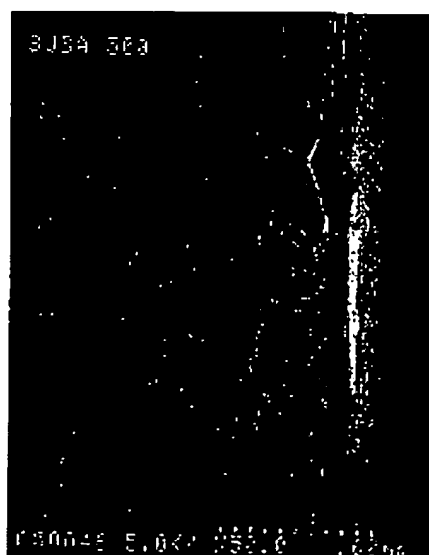
Fig. 6.2. Surface of a Type 1 Pad (Suba 500™)

the type of polyurethane and the amount of residual porosity, a family of pads is possible differing in compressibility, hardness and stiffness.

Figures 6.3 and 6.4 show the cross-section and surface microstructures respectively of a Type 2 pad, as exemplified by UR100™. This type of pad has the most complex microstructure consisting of a porous layer on a supporting substrate similar in structure to a Type 1 pad. Type 2 pads are among the earliest pads used for polishing and their origin dates back to the Corfam™ process developed by Dupont in the 1950's to make microporous, permeable artificial leather [14]. It is interesting to note that real leather was used during the early days of semiconductor technology to polish silicon wafers. Type 2
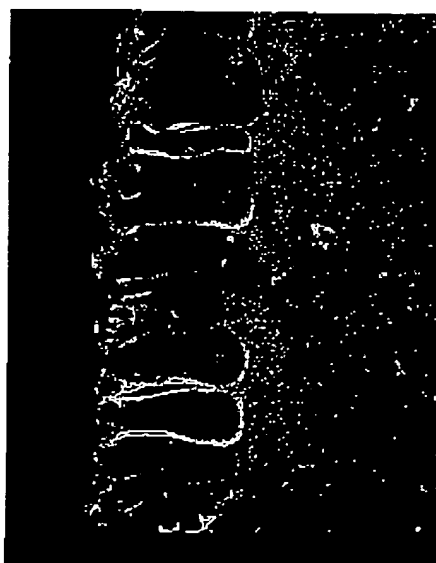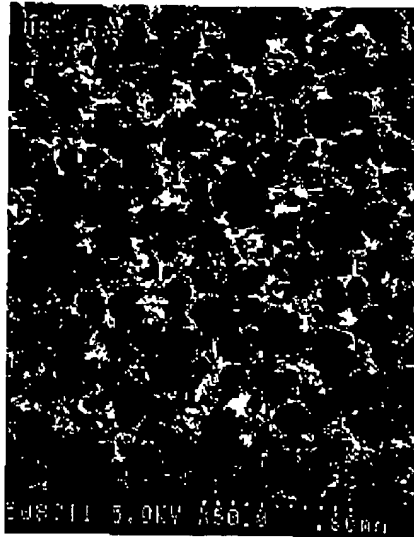
Fig. 6.4. Surface of a Type 2 Pad (UR100™)

pads are generically known as "poromerics" arising from the fact that these materials are *poro*us and poly*meric*. The surface of the pad consists of open pores which can hold and transport slurry across the pad surface.

Figures 6.5 and 6.6 show the cross-section and surface microstructures respectively of a Type 3 pad, as exemplified by IC1000™. This type of pad is essentially a closed cell foam, where the pores are created either by blowing agents or by the addition of micro-balloons. Since the pads are porous and made by mechanically machining individual pads, the pad surface has significant texture even prior to conditioning.
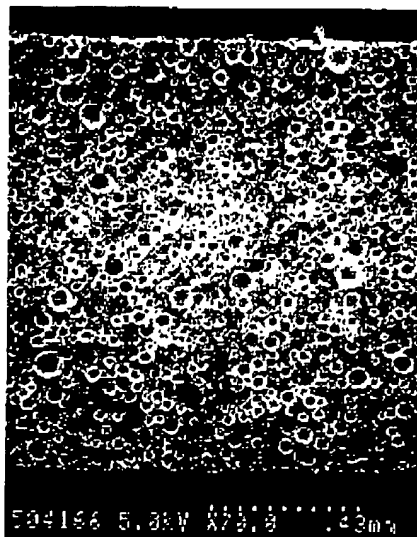
178   David B. James
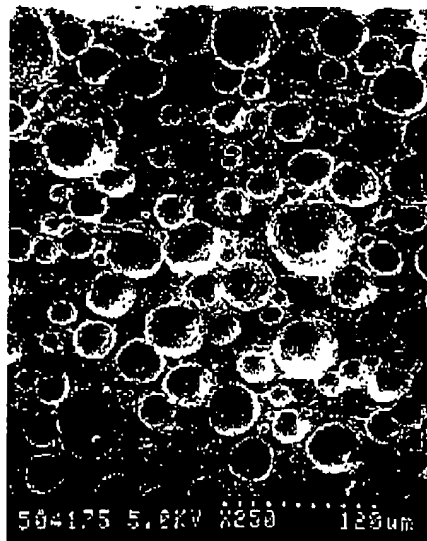
Fig. 6.6. Surface of a Type 3 Pad (IC1000™)
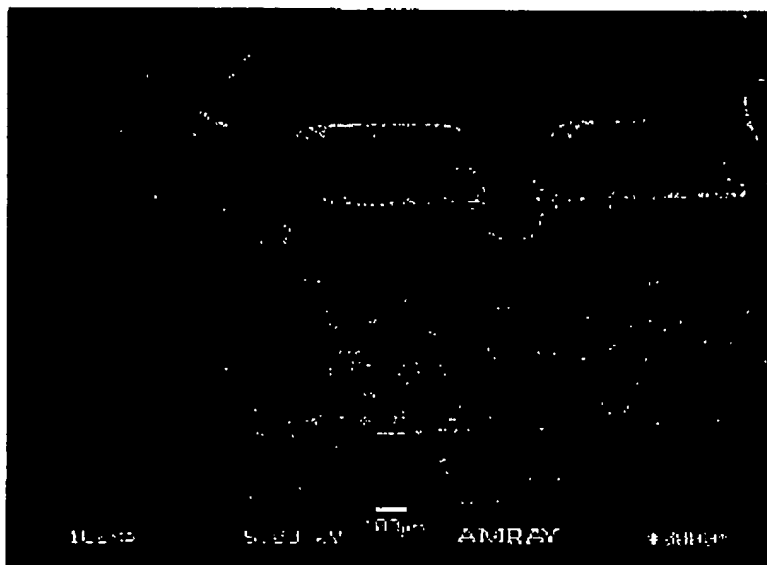
Fig. 6.7. Cross-section of a Type 4 Pad (OXP3000™)

Figures 6.7 and 6.8 show the cross-section and surface microstructures respectively of a Type 4 pad, as exemplified by OXP3000™. This type of pad has the simplest microstructure, being non-porous and unfilled. With such pads, it is known [15] that it is essential to have both macro- and microtexture to achieve acceptable polishing. As shown in Fig. 6.7, macrotexture consists of grooves formed in the pad surface either by mechanical machining as a post-processing step or by net-shape processing.

Type 3 and Type 4 pads are usually used in combination with an un-
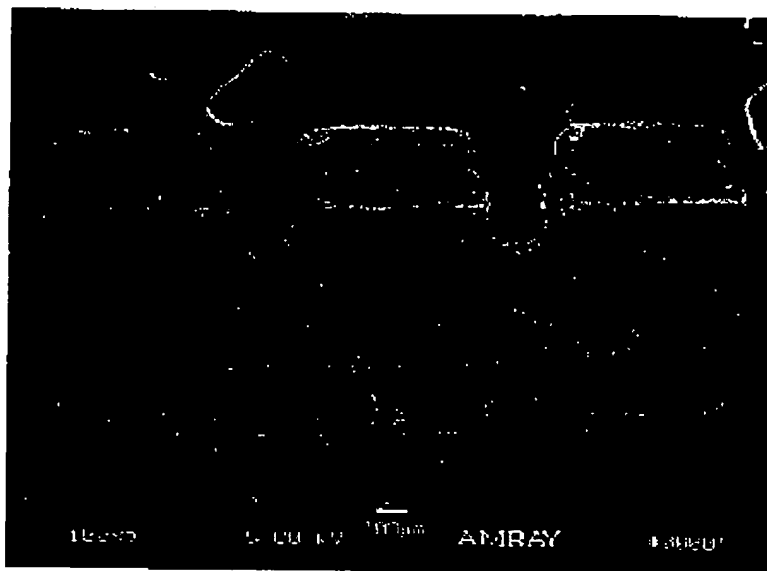
Fig. 6.8. Surface of a Type 4 Pad (OXP3000™)

uniformity across the wafer caused by non-planarity of the top-pad and polishing tool deficiencies. Base-pads are typically of higher compressibility and lower stiffness than the top-pads and thus act essentially as supporting "cushions" for the top-pad. Figures 6.9 and 6.10 show cross-sections of two types of base-pads commonly used for CMP polishing. Figure 9 is an example of an impregnated polyester felt (SubaIV™), similar to Type 1 pads discussed above but with higher compressibility and porosity. Figure 10 is an example of a polyurethane closed cell elastomeric foam.

Fig. 6.9. Cross-section of a SUBA IV™ Base Pad

180   David B. James

Fig. 6.10. Cross-section of a Closed Cell Foam Base Pad

6.5 Control of Polyurethane Pad Properties

This section will explore approaches available to control the properties of polishing pads. The focus will be on Type 3 and Type 4 pads, since they are commercially of most significance, but the approaches are also applicable to the other pad types. Approaches are:
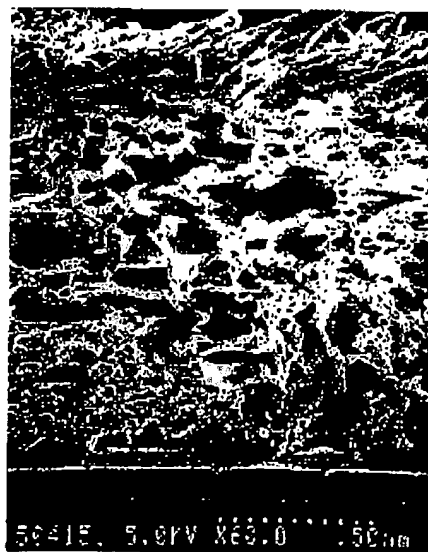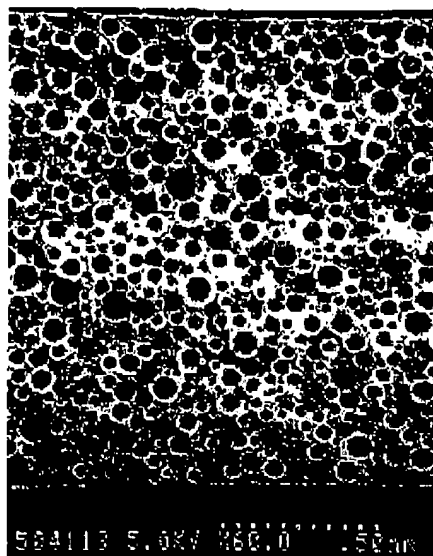
   i. Control of hard and soft segments
  ii. Urethane stoichiometry
 iii. Pad thermal history
  iv. Amount of porosity.

Each of these will be discussed in detail and illustrated with examples.

6.5.1 Hard and Soft Segments

Previously in this chapter, the concept of hard and soft segments in polyurethanes was discussed. The type and concentration of these segments are major factors in controlling pad properties. Typically, increasing the soft segment concentration increases toughness and flexibility but reduces modulus and hardness. The hard segments, which usually soften at temperatures above ambient, improve high temperature properties and increase properties such as stiffness and strength.

The ability to manipulate pad properties through control of hard and soft segments is illustrated in Figs. 6.11 and 6.12. These are ternary phase diagrams for a three component polyurethane formulation. Each point within the triangle represents a specific composition. Figures 6.11 and 6.12 show
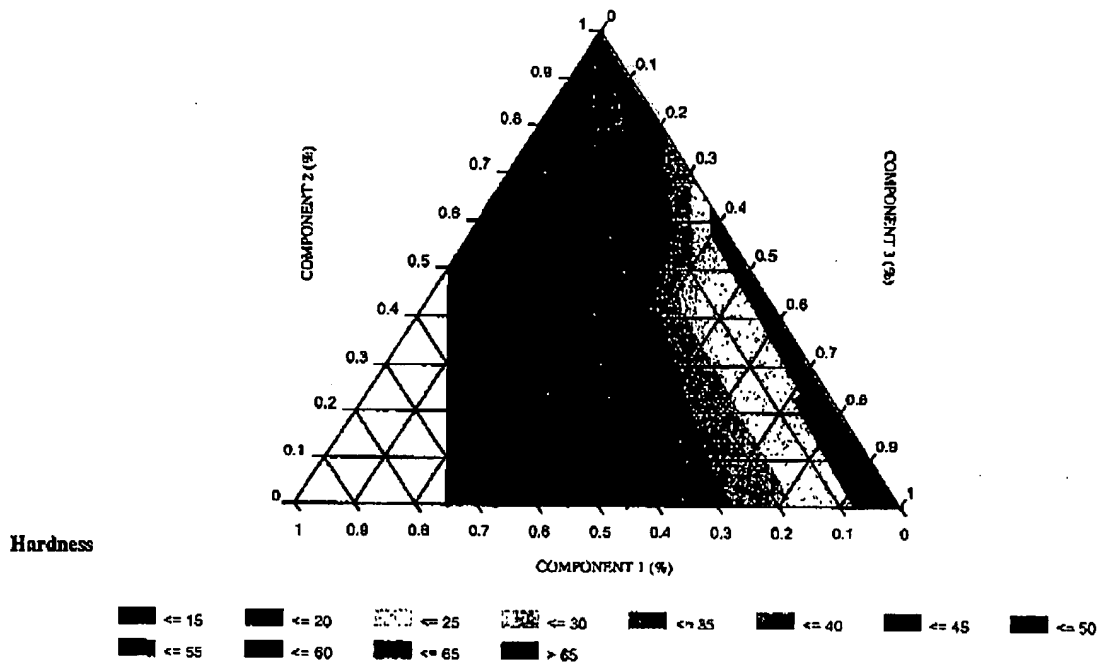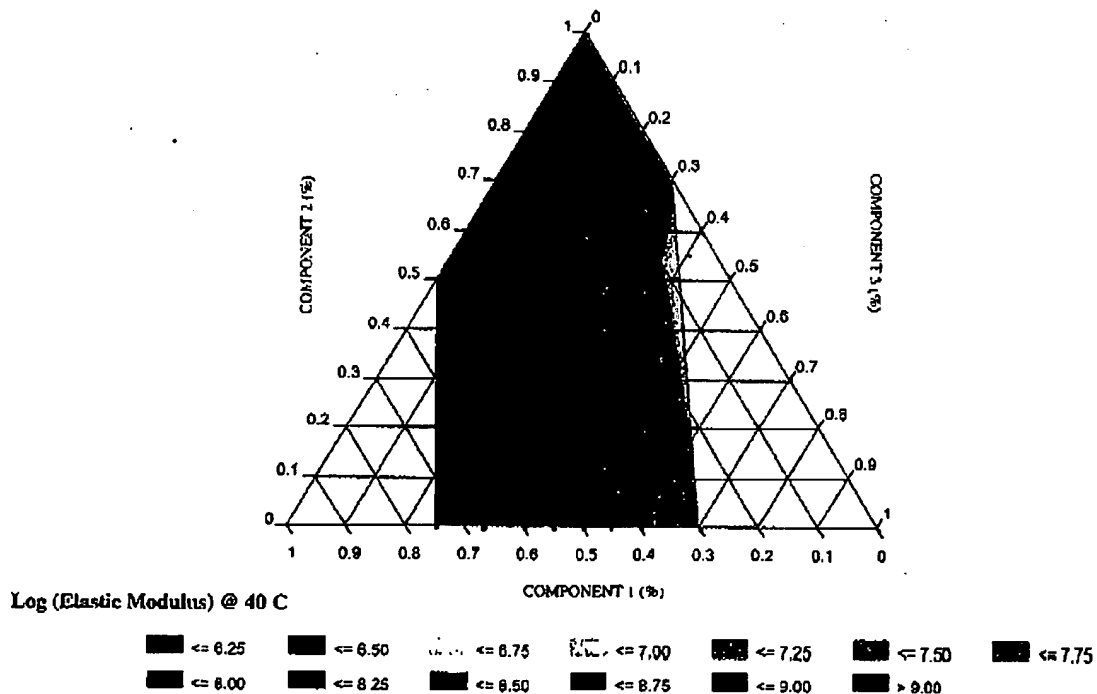
Fig. 6.11. Hardness as a Function of Composition

Fig. 6.12. Modulus as a Function of Composition

Figure 6.11 shows that it is possible to vary hardness from Shore D values of less than 15 to greater than 65. This covers the practical range of interest for all types of polishing pads. In general, harder pads are used for lower

182   David B. James

and conductors. Slightly softer pads are used for polishing copper damascene features, and still softer pads are used in final buff polishing to remove defects from the earlier steps.

Figure 6.12 shows a similar diagram for modulus. In fact, the diagram shows the logarithm of modulus, again illustrating the broad range of properties achievable through hard and soft segment control. In Fig. 6.12, modulus varies by three orders of magnitude from rigid, stiff pads to pads that are very flexible and elastomeric. As will discussed later, stiffer pads are preferred for those polishing applications where planarization is important. A comparison of Figs. 6.11 and 6.12 shows that hardness and modulus follow similar behavior with composition. Although it is often the case that hardness increases with increasing modulus, as will be seen in the next section, it is also possible to control them somewhat independently.

6.5.2 Urethane Stoichiometry

Stoichiometry refers to the ratio of reactive groups, usually diol or diamine moieties, to isocyanate groups. A stoichiometry of 100% indicates a perfect balance between isocyanate and diol groups. However, as mentioned earlier, it is customary with polyurethanes to use an excess of isocyanate and values of 85 to 95% are more typical. The reason for this is to take advantage of the side reactions that can take place when excess isocyanate is present. These are used to further control pad properties. A ratio of exactly 100% would result in a linear high molecular polymer [16]. Since isocyanate groups also react with moisture, exact stoichiometric balance is difficult to achieve and consequently this makes molecular weight control difficult, especially in a production environment.

Table 6.5 illustrates the effect of stoichiometry for an experimental, nonporous Type 4 pad. As the stoichiometric ratio increases, the amount of excess isocyanate and the number of side reactions decrease. Since many of these side reactions result in chemical bonds (known as cross-links) between polymer chains, the polyurethane transitions from a predominantly thermosetting network polymer to a more linear polymer, having more thermoplastic behavior, as stoichiometry increases.

Table 6.5. Effect of Stoichiometry on Pad properties

Property	Stoichiometry (%)		
	75	85	95
Hardness (Shore D)	60.5	61.2	63.4
Tensile Strength (MPa)	65.0	67.1	80.5
Elongation to Break (%)	281	298	459

As stoichiometry increases, hardness, tensile strength and elongation increase, consistent with a decrease in cross-links and an increase in ductility. Modulus decreases since cross-links increase rigidity. A comparison of the trend of hardness and modulus with stoichiometry shows that this is an example where it is possible to control hardness and modulus independently.

6.5.3 Pad Thermal History

The properties of polyurethanes are strongly influenced by their thermal history. In this context, thermal history includes the temperatures and times at which the pads are initially cured and, where appropriate, subsequently postcured. Optimum times and temperatures will depend on the specific urethane system. However, for thermosetting polymers, which includes polyurethanes, it is generally accepted [16] that increasing baking temperatures and time at temperature will increase the degree of cure and change physical properties.

Table 6.6 illustrates the effect of thermal history on polyurethane properties for an unfilled Type 4 pad. Baking conditions have been designated as low, medium and high. High signifies a longer bake at higher temperature than medium, and medium versus low have the same relationship to one another. As baking conditions increase, pad properties such as hardness and modulus increase and elongation decreases. These trends are consistent with the formation of more cross-links between polyurethane chains producing a network structure and, relatedly, to an increase in the glass transition temperature (T_g) of the polyurethane.

T_g is the temperature at which the polyurethane softens appreciably. One method to measure T_g from the peak value of the tan delta damping curve as measured by dynamic mechanical analysis [17]. Tan delta is a measure of the damping ability of a material and is discussed in more detail later in this section. Figure 6.13 shows the effect of baking conditions on the tan delta curves for this urethane system. As baking conditions increase, the peak in tan delta

Table 6.6. Effect of Thermal History on Polyurethane Properties

Property	Baking Conditions		
	Low	Medium	High
Density (g/cm^3)	1.183	1.184	1.184
Hardness (Shore D)	70.5	71.2	73.9
Yield Strength (MPa)	29.4	31.6	36.1
Tensile Strength (MPa)	63.7	62.1	68.0
Elongation to Break (%)	340	320	250
Glass Transition Temperature (°C)	65	68	77

184 David B. James

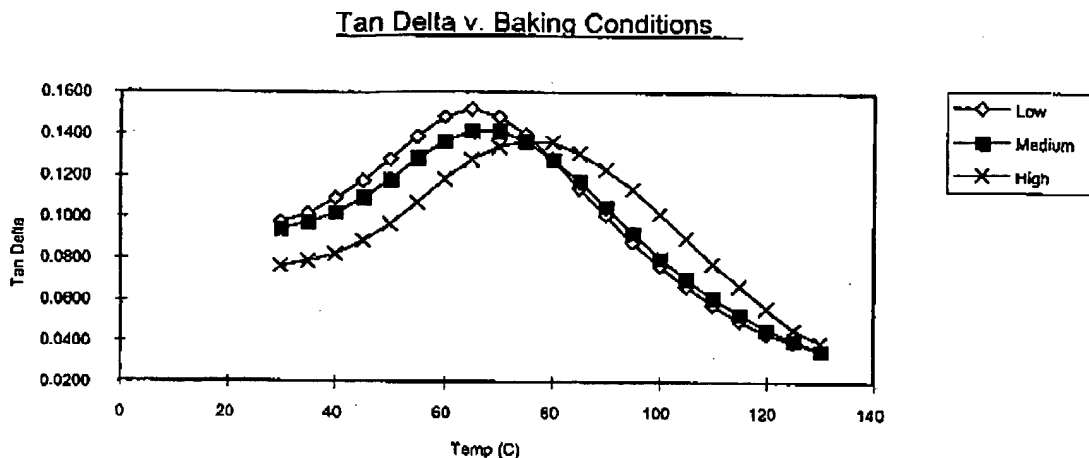## Tan Delta v. Baking Conditions

Fig. 6.13. Effect of Baking Conditions on Tan Delta

shifts to higher temperatures and slightly broadens. At more aggressive baking conditions, the tan delta curves will broaden further, signifying the onset of thermal degradation and a deterioration in pad properties. When selecting baking conditions, it is important to select times and temperatures which optimize properties for the specific application without causing degradation.

It is appropriate at this point to make a brief mention of the technique of dynamic mechanical analysis to study polishing pads. Since polishing is a dynamic process involving cyclic motion of both the polishing pad and the wafer and since polymeric polishing pads are viscoelastic materials, a valuable method of studying pad properties is by dynamic mechanical analysis [17]. In this technique, a cyclic deformation is applied to the sample at temperatures and frequencies that correspond to typical polishing conditions.

Viscoelastic materials exhibit both viscous and elastic behavior in response to an applied deformation. The resulting stress signal can be separated into two components: an elastic stress which is in phase with the strain, and a viscous stress which is in phase with the strain rate but 90 degrees out of phase with the strain. The elastic stress is a measure of the degree to which a material behaves as an elastic solid; the viscous stress, the degree to which the material behaves as an ideal fluid. The elastic and viscous stresses are related to material properties through the ratio of stress to strain, the modulus. Thus, the ratio of elastic stress to strain is the storage (or elastic) modulus and the ratio of the viscous stress to strain is the loss (or viscous) modulus. When testing is done in tension or compression, E' and E'' designate the storage and loss modulus, respectively.

The ratio of the loss modulus to the storage modulus is the tangent of the phase angle shift (δ) between the stress and the strain. Thus,

$$E''/E' = \tan\delta$$

With specific reference to polishing, energy is transmitted to the pad during the polishing cycle. A portion of this energy is dissipated inside the pad as heat and the remaining portion of this energy is stored in the pad and is subsequently released as elastic energy during the polishing cycle.

6.5.4 Pad Porosity

Although the morphologies of Type 1, 2 and 3 pads differ, they all contain porosity which plays a key role in determining pad physical properties and polishing functionality. For these pads, porosity is needed to retain slurry on the pad surface and to distribute slurry uniformly across that surface. In this section, the importance of porosity will be illustrated using data for IC1000™ and IC2000™.

Table 6.7 shows typical physical properties of IC1000™, Style 5.

Many of these properties are strongly dependent on the porosity present in the pad. For these pads, porosity is difficult to measure directly with a high degree of accuracy. Instead, porosity is most conveniently determined quantitatively by measuring pad density, since the two are related by the equation:

$$\text{Volume Fraction Porosity} = \frac{\text{Density of Bulk Polymer} - \text{Density of Pad}}{\text{Density of Bulk Polymer}}.$$

Table 6.8 shows the statistical correlations between pad density and other physical properties. It is apparent that the correlations are very high (± 1.00 being a perfect correlation). Since many properties depend on pad porosity and are not independent of one another, as will be seen in a later section,

Table 6.7. Typical Physical Properties of IC1000™

Property	Value
Porosity (# of cells)	880 ± 120
Density (g/cm^3)	0.748 ± 0.051
Hardness (Shore D)	52.2 ± 2.5
Shear Strength (MPa)	51.2 ± 4.1
Proportional Limit (MPa)	9.1 ± 1.3
Tensile Strength (MPa)	21.6 ± 2.8
Elongation to Break (%)	175 ± 20
Storage Modulus (MPa)	310 ± 40
Loss Modulus (MPa)	28.0 ± 4.5
Tan Delta	0.090 ± 0.005

186   David B. James

Table 6.8. Relationship between Pad Density and other Physical Properties

Pad Physical Property	Correlation Coefficient
Porosity	−0.77
Hardness	0.94
Shear Strength	0.84
Proportional Limit	0.88
Tensile Strength	0.96
Elongation to Break	0.80
Storage Modulus	0.89
Pad Stiffness	0.88

relating specific pad properties to polishing performance is made even more complex.

Figures 6.14 and 6.15 graphically show the linear relationships of density with hardness and storage modulus respectively.

It has been shown above that porosity has a strong influence on other pad properties. A consequence of this relationship is that porous pads have more variability in physical properties than equivalent non-porous pads. This may be illustrated by comparing the physical property distributions of IC1000™ and IC2000™. IC2000™ is very similar to IC1000™ and made by the same manufacturing process but is non-porous. Typical physical properties of IC2000™ are shown in Table 6.9.

Figure 6.16 compares the key physical properties for the two pad types in terms of the ratio of standard deviation to property average [18, 19]. It is
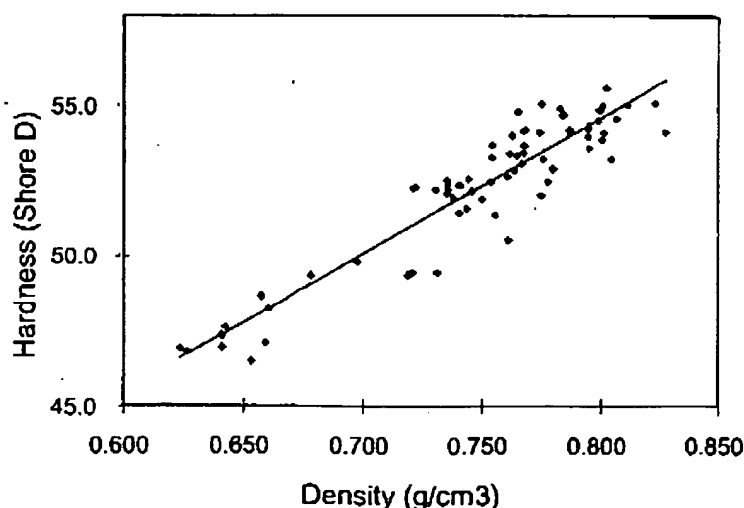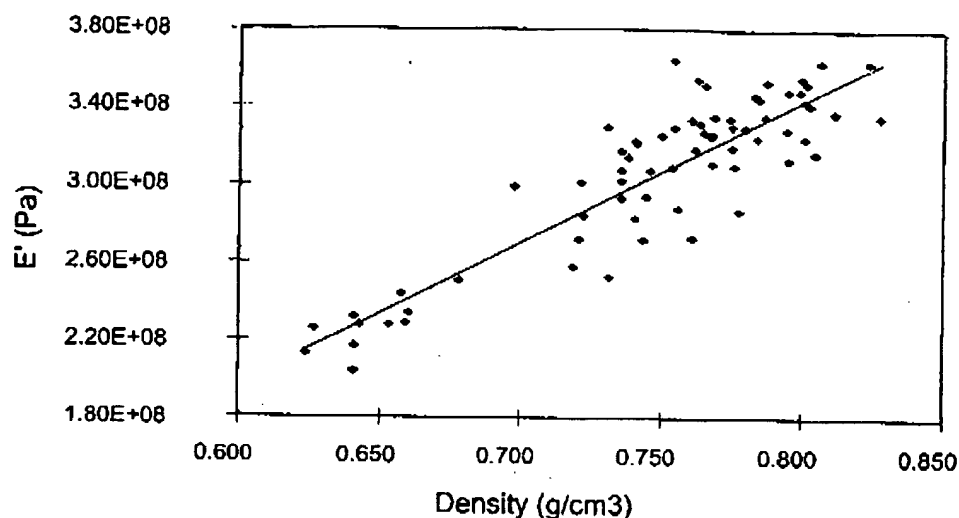
Fig. 6.15. Storage Modulus versus Density for IC1000™

Table 6.9. Typical Physical Properties of IC2000™

Property	Value
Porosity (# of cells)	0
Density (g/cm³)	1.180 ± 0.002
Hardness (Shore D)	73.0 ± 1.0
Yield Strength (MPa)	33.4 ± 1.4
Tensile Strength (MPa)	75.0 ± 2.5
Elongation to Break (%)	335 ± 20
Storage Modulus (MPa)	850 ± 61
Loss Modulus (MPa)	87.0 ± 4.0
Tan Delta	0.103 ± 0.005

clearly evident that for non-porous pads the variability in density is significantly less and that a similar trend is present in the other properties shown.

An advantage of non-porous pads is thus a much tighter distribution of physical properties. Although the relationships between polishing performance and pad physical properties are not well understood, a tighter property distribution should translate into more consistent polishing performance. This may be illustrated for oxide polishing using the two pad types [18]. Figure 6.17 shows the distribution of removal rate for a large number of wafers polished using either IC1000™ or IC2000™. Conditioning was kept constant for the two pad types. The distribution of removal rate is much tighter for the non-porous pad, consistent with the above discussion.

In addition to the benefit of more consistent pad physical

188   David B. James

Physical Property Variability of IC1000 and IC2000
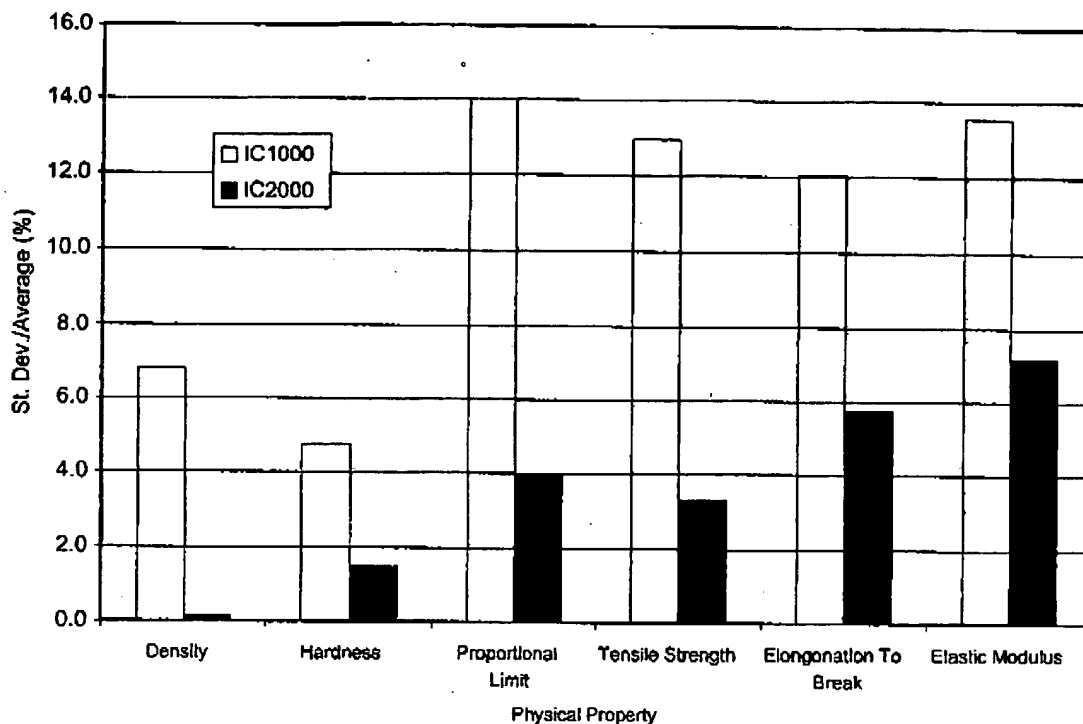
Fig. 6.16. Effect of Porosity on Variability of Pad Properties
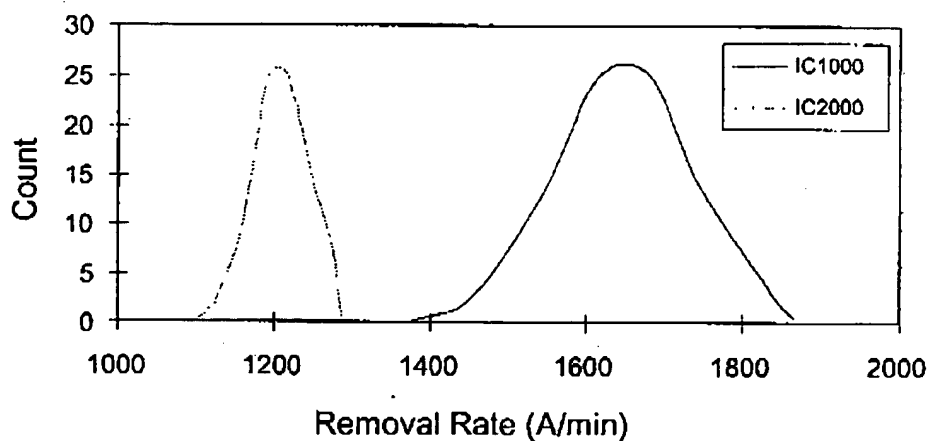
Fig. 6.17. Effect of Pad Porosity on Polishing Removal Rate Distribution

porous pads. Typically, as may be seen by comparing the property data for IC1000™ and IC2000™ shown in Tables 6.7 and 6.9 respectively, non-porous pads have a higher modulus. This translates to improved planarization of die-scale features during polishing. Abrasion resistance of non-porous pads also tends to be higher which results in less pad wear during polishing

been demonstrated for copper CMP polishing, is reduced defectivity [20, 21]. Pores on the pad surface can trap polishing debris which can either scratch the wafer features, especially if the features are soft materials like copper, or leave residual particles on the wafer surface.

There are also challenges with non-porous pads. The primary challenge is that non-porous pads require more rigorous pad break-in to achieve optimum polishing performance. It is well-known [15] that for effective polishing, the pad surface must have both micro- and macro-texture. The latter is discussed in detail in the next section. Micro-texture refers to the roughness of the pad surface and the presence of asperities which contact the wafer during polishing. During pad break-in, the surface of the pad is roughened using typically a diamond impregnated conditioning tool. With porous pads, the pores in the pad surface inherently create a surface which is initially rougher than the surface of a non-porous pad, so conditioning is effectively given a head-start. In contrast, with non-porous pads, the initial surface is much smoother and all the micro-texture must be created by the conditioning process. Thus, non-porous pads require a longer conditioning break-in cycle and the removal rate decay observed when abrasive conditioning is stopped during polishing is higher [18].

The second challenge is "edge effects" during polishing which increase removal rate non-uniformity across the wafer surface by leaving a thicker ring of polished material around the wafer edge. This reduces the usable area of the wafer surface. Edge effects have been discussed by Baker [22], and related to the physical properties of the top and base layers of a polishing pad. Baker's modeling work, and subsequent experimental validation, shows that as the stiffness of the top pad increases, edge effects also increase. Since non-porous pads are stiffer than corresponding porous pads, edge effects would be expected to be more of a problem with the non-porous pads and this has been verified experimentally using IC2000^{TM}. However, edge effects can be largely eliminated by the use of retaining rings on the wafer carrier that are essentially coplanar with the wafer surface. This approach has been implemented with beneficial results by several polishing tool manufacturers. A second approach to minimize edge effects is through the judicious use of macro-grooves in the top pad which reduce pad stiffness in a controlled way without compromising die-scale feature planarity [62].

6.6 Control of Pad Properties Through Pad Geometry

The previous section discussed control of pad properties through the pad urethane chemistry and formulation. This section discusses the manipulation of pad properties by physical control of the pad geometry. This includes consideration of pad thickness, groove designs, pad shapes, and base pad.

190   David B. James

6.6.1 Pad Thickness

Top pad thickness is important, since it determines the stiffness of the pad, given that pad stiffness is proportional to the product of pad modulus and cube of the thickness [23]. Thus doubling the pad thickness increases stiffness eight-fold. Polishing pads used for CMP are typically about 1.3 mm (50 mil) thick. Pad stiffness controls several important polishing parameters, including uniformity of removal rate across the wafer, die level planarity, and to a lesser extent dishing and erosion of features within a die. In order to planarize next generation devices, pad thicknesses greater than 1.3 mm (50 mil) are preferred, and 2.0 mm (80 mil) thick pads are now being used routinely by several major semiconductor manufacturers. Above about 5 mm (200 mil), polishing uniformity may suffer because of the inability of the pad to conform to variations in global wafer flatness.

As a polishing pad wears, the overall pad thickness and corresponding stiffness decrease. This again argues for a high initial pad thickness, as the change in stiffness with polishing time will be relatively less for a thicker pad. Additionally, since stiffness is less dependent on the grooved thickness, which is removed during pad use, rather than the underlying ungrooved region, high thickness for the underlying ungrooved layer and for the overall pad are preferred.

For a given pad thickness, increasing pad modulus will increase pad stiffness and the ability of the pad to planarize. Thus, as mentioned previously, unfilled pads will planarize more effectively than filled pads. However, it is important to recognize that stiffness is proportional to the cube of thickness compared to only the single power of modulus, so that changing pad thickness can have a more significant impact than changing pad modulus.

Figure 6.18 [64] shows the effect of pad thickness on oxide planarity for a Type 4 experimental pad (OXP3000™ from Rodel). The polisher was a Strasbaugh 6DS-SP and the slurry was ILD1300™ also from Rodel. The figure shows planarity expressed as "planarity quotient" for different feature sizes. Planarity quotient is defined as the oxide removal rate at the bottom of a feature trench divided by the oxide removal at the top of a feature. Thus, the smaller the planarity quotient, the more efficient the planarization process. Since smaller features are more readily planarized, planarity quotient increases with increasing feature size. For a given value of planarization quotient, the feature size corresponding to that value may be defined as the "planarization distance". Longer planarization distances indicate enhanced ability of a pad to planarize.

Figure 6.18 shows that for a given value of planarization quotient, polishing with a 2.0 mm (80 mil) thick pad results in a higher planarization distance versus the 1.3 mm (50 mil) thick pad. For example, at an arbitrary planarization quotient of 0.3, the 2.0 mm (80 mil) thick pad has a planariza-
tion distance of about 40% longer than the distance for the 1.3 mm (50 mil)
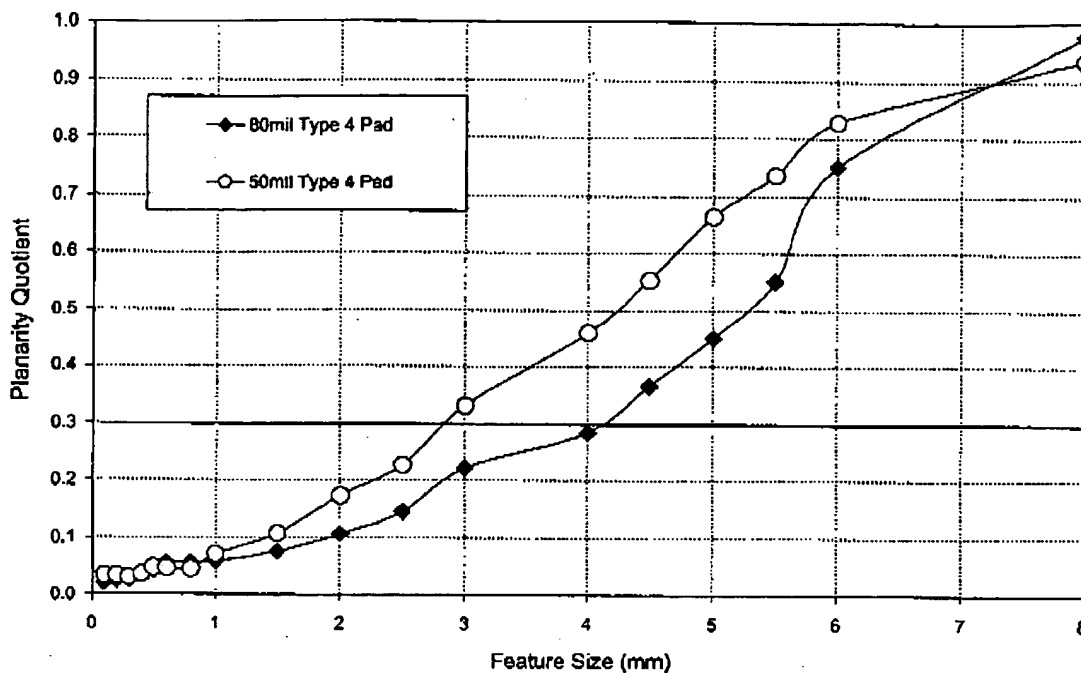
Fig. 6.18. Effect of Pad Thickness on Planarity

As discussed in the next section, grooving the surface of polishing pads also affects pad stiffness. In general, the deeper the grooves with respect to pad thickness and the closer the grooves are to one another, the more flexible the pad.

6.6.2 Groove Designs

Polishing pads used for chemical mechanical polishing typically have macro-texture. This can be either perforations through the pad thickness or surface groove designs. Such surface designs include, but are not limited to, circular grooves which may be concentric or spiral grooves, cross-hatched patterns arranged as an X-Y grid across the pad surface, other regular designs such as hexagons, triangles and tire-tread type patterns, or irregular designs such as fractal patterns, or combinations thereof. The groove profile may be rectangular with straight side-walls or the groove cross-section may be "V"-shaped, "U"-shaped, triangular, saw-tooth, etc. Further, the geometric center of circular designs may coincide with the geometric center of the pad or may be offset. Also the groove design may change across the pad surface. The choice of design depends on the material being polished and the type of polisher, since different polishers use different size and shape pads (i.e. circular versus linear).

Table 6.10 provides an overview of the multitude of groove designs that

192   David B. James

Table 6.10. US Patents covering Groove Designs

US Patent Number	Description of Groove Design
5,020,283	Achieve constant surface area across pad using circular voids, holes, squares and ray designs
5,177,908	Sun-burst pattern of non-tapered rays
5,216,843	Circumferential triangular macro-grooves and conditioning microgrooves
5,297,364	Circular voids to control non-uniformity
5,329,734	Regions of different circular pore density
5,394,655	Annular rings with tapered cross-section
5,489,233	Non-porous pads having macro and micro-channels
5,578,362	Type 3 pads with circular and X-Y groove designs
5,609,719	X-Y channels with slurry recesses at intersections to minimize edge exclusion
5,628,862	Molded pad surface comprising channels between hemispherical features
5,645,469	Radially extending tapered channels and circumferential grooves
5,650,039	Off-center circular spiral groove
5,690,540	Inward spiral from pad periphery to center
5,725,420	Combination of holes and X-Y grooves where groove pitch > hole pitch
5,778,481	Spiral, swirl or concentric raised areas direct fluids from pad center to edge
5,842,910	Circumferential grooves offset from pad geometric center
5,888,121	Regions with different circular and X-Y groove dimensions
5,900,164	Type 3 pads with circular and X-Y groove designs
5,921,855	Circular, spiral or concentric grooves
5,984,769	Regions with different circular groove dimensions

Grooves are added to polishing pads used for CMP for several reasons:

1. To prevent hydroplaning of the wafer being polished across the surface of the polishing pad. If the pad is either ungrooved or unperforated, a continuous layer of polishing fluid can exist between the wafer and pad, preventing uniform intimate contact and significantly reducing removal rate.

2. To ensure that slurry is uniformly distributed across the pad surface. [2.]

cially important when polishing reactive metals such as copper, in which the chemical component of polishing is as critical as the mechanical. Uniform slurry distribution across the wafer is required to achieve the same polishing rate at the center and edge of the wafer. However, the thickness of the slurry layer should not be so great as to prevent direct pad-wafer contact.

3. To control both the overall and localized stiffness of the polishing pad. This controls polishing uniformity across the wafer surface and also the ability of the pad to level features of different heights to give a highly planar surface. Different regions of the pads may have different groove designs.

4. As a subset of 3, to reduce edge effects.

5. To act as channels for the removal of polishing debris from the pad surface. A build-up of debris increases the likelihood of scratches and other defects. This is related to 2, since as new slurry replaces the old, the old removes the entrained debris.

It is known [15, 25] that one factor determining pad-life of grooved pads is the depth of the grooves, since acceptable polishing performance is possible only until the pad has worn to the point where grooves have insufficient depth to distribute slurry, remove waste, and prevent hydroplaning. For Type 3 pads containing porosity, the minimum groove depth to prevent hydroplaning is about 3 mil and for Type 4 non-porous unfilled pads about 5 mil. In order to achieve the combination of acceptable pad stiffness and long pad-life, it is necessary to have deep grooves but also sufficient remaining pad to provide stiffness. As groove density and groove width increase, pad stiffness becomes more dependent on the thickness of the remaining ungrooved layer of the pad, rather than on groove depth alone.

6.6.3 Pad Shapes

The patent literature contains many examples of novel pad shapes which have been proposed to improve polishing performance. Although many of these concepts are untested, they illustrate some of the options that may be used to optimize polishing performance through control of pad geometry. Table 6.11 summarizes some of the key patents covering pad shape. This list is by no means complete but illustrates some of the approaches that are being considered.

6.6.4 Base Pads

Ideally, for uniform polishing, removal rate should be the same at all points on the wafer surface. This would suggest that the pad needs to be in contact

194   David B. James

Table 6.11. US Patents related to Pad Shape

US Patent #	Assignee	General Area	Brief Description
5,310,455 5,516,400 5,624,304	LSI	Extended Pad Edge	A lower pad is mounted to the platen and is trimmed to the size of the platen. An upper pad is mounted to the lower pad, and is sized so that an extreme outer edge portion of the upper pad extends beyond the trimmed outer edge of the lower pad. The outer edge portion of the upper pad is deformed downwardly, towards the lower pad. In this manner, polishing slurry is diverted from the pad-to-pad interface. Additionally, an integral annular lip can be formed on the front face of the upper pad, creating a reservoir for slurry to be retained on the face of the upper pad for enhancing residence time of the polishing slurry prior to the slurry washing over the face of the upper pad.
5,234,867 5,421,769	Micron	Non-circular Pads	A polishing head mechanism moves the polishing head and semiconductor wafer across and past a peripheral edge of a non-circular pad to effectuate a uniform polish of the semiconductor wafer surface.
5,558,563	IBM	Raised Areas	A polishing pad which includes raised portions is used to apply varying amounts of pressure. In addition, the position, size and height of the raised portions are used to affect the amount of pressure applied. There are several possible methods to produce raised areas in the polishing pad. In particular, shims can be added to the polishing table or the polishing table can be machined so that the polishing table includes raised portions.
5,785,584 5,934,977	IBM	Raised Areas	The rotating polishing pad is caused to flex upward as it passes over a discrete, non-continuous "bump formed in the surface of an underlying stationary platen. This deflection in any given portion of the pad is a transient condition as the raised portion of the pad will fall back from to its original configuration once it clears the underlying bump. Thus, portions of the pad will be continuously progressed up, over and back down to create a discrete raised portion in the polishing pad surface at a fixed location.
5,888,126	Ebara	Raised Areas	The abrasive cloth has a projecting region on a surface thereof for more intensive contact with the workpiece than other surface regions of the abrasive cloth. Projecting regions on the pad surface are effected by creating projecting regions in the underlying upper surface of the turntable using actuators which may be electromagnetic, piezoelectric or compressed air.
5,769,699	Motorola	Multiple Regions	The polishing pad has a first region that is closer to the edge of the polishing pad and a second region adjacent to the first region and further from the edge of the polishing pad. The polishing pad is configured, so that the second region is thicker or less compressible compared to the first region.
5,738,567 5,910,043	Micron	Multiple Regions	The polishing pad has a polishing body and a cleaning element positioned in the polishing body. In operation, the cleaning surface periodically engages the wafer when the wafer is engaged with the pad to remove residual materials

Table 6.12. Patents describing Multiple Layer Pads

Patent #	Assignee	Brief Description
US5,212,910	Intel	Three layer composite pad, comprising a top polishing layer, an intermediate stiff layer which may be segmented to create a "bedspring" effect, and a bottom elastic cushioning layer.
US,5257,478	Rodel/ Westech	Pad has at least two layers, wherein the base layer is more compressible than the top planarizing layer.
US5,287,663	National Semiconductor	Three layer composite pad, comprising a top polishing layer, an intermediate rigid layer and a bottom resilient layer.
US5,564,965	SEH	Three layer composite pad, comprising a top polishing layer, an intermediate rigid layer and a closed-cell foam of soft rubber as the bottom layer.
US5,664,989	Toshiba	Two layer polishing pad, wherein the base layer consists of fine bags hermetically sealed with fluid to provide uniform pressure distribution across the wafer.
US5,871,392	Micron	Base pad contains a plurality of thermal conductors to conduct heat from the polishing layer to the platen.
US5,876,269	NEC	Two layer polishing pad comprising an upper polishing layer harder than the lower layer
US5,893,755	Komatsu	Discloses silicon rubber base pad to reduce waviness during polishing.
US5,899,745	Motorola	Base pad has an edge and central portion, such that the compressibility of the center portion is higher than that of the edge.
US5,899,799	Micron	Grooved base pad which creates depressions in the upper pad for control of slurry flow across the polishing pad.
EPA845,328	Sumitomo	Three layer composite pad, comprising a top porous polishing layer, an intermediate support layer and a bottom resilient layer.
EPA919,336	Speedfam	Two layer pad comprising a top pad over a more compressible base pad, such that both are uniformly permeable to polishing fluid.

196   David B. James

perfectly flat and typically have some degree of curvature resulting from the stresses of manufacture and differing coefficients of thermal expansion of the various deposited oxide and metal layers. This requires the polishing pad to have sufficient flexibility to conform to wafer-scale flatness variability. One solution to this problem is to laminate a stiff polishing pad to a flexible underlying base pad, which is typically a more compressive, foam-type polymeric material. This improves polishing uniformity across the wafer without unduly compromising the stiffness of the polishing top pad.

Several patents have recently been issued disclosing the use of polishing pads, wherein the top pad, which contacts the wafer, is laminated to at least one underlying pad. This base pad is typically more compressible than the top pad. In some cases, a thin but stiffer intermediate layer is sandwiched between top and base pads. Table 6.12 summarizes some of the main patents covering multiple layer pads.

Table 6.13 shows physical properties of two commonly used base pads. The microstructures of these base pads have been shown previously in Figs. 6.9 and 6.10. Suba IV^{TM} is a polyurethane impregnated felt and the other base pad is a closed cell polyurethane foam.

As discussed previously, Suba IV^{TM} and foam base pads have very different microstructures. The effect of microstructure on physical properties is that the properties of Suba IV^{TM} are anisotropic, whereas those of the foam are isotropic. The properties shown above are measured through the thickness of the pad rather than in the plane of the pad. The porosity in Suba IV^{TM} is essentially open which can lead to wicking of slurry into the base pad.

Figure 6.19 [64] shows the effect of base-pad on the planarity of oxide features, polished with a Type 4 experimental pad (OXP3000^{TM} from Rodel). The polisher was a Strasbaugh 6DS-SP and the slurry was ILD1300^{TM} also from Rodel. Three sets of data are shown, corresponding to no base pad, Suba IV^{TM}, and an experimental foam base pad similar in microstructure and properties to the foam base pad discussed above.

It is clearly evident that the best planarity is achieved with no base pad. However, polishing uniformity across the wafer is poor caused by imperfect

Table 6.13. Typical Physical Properties of Base Pads

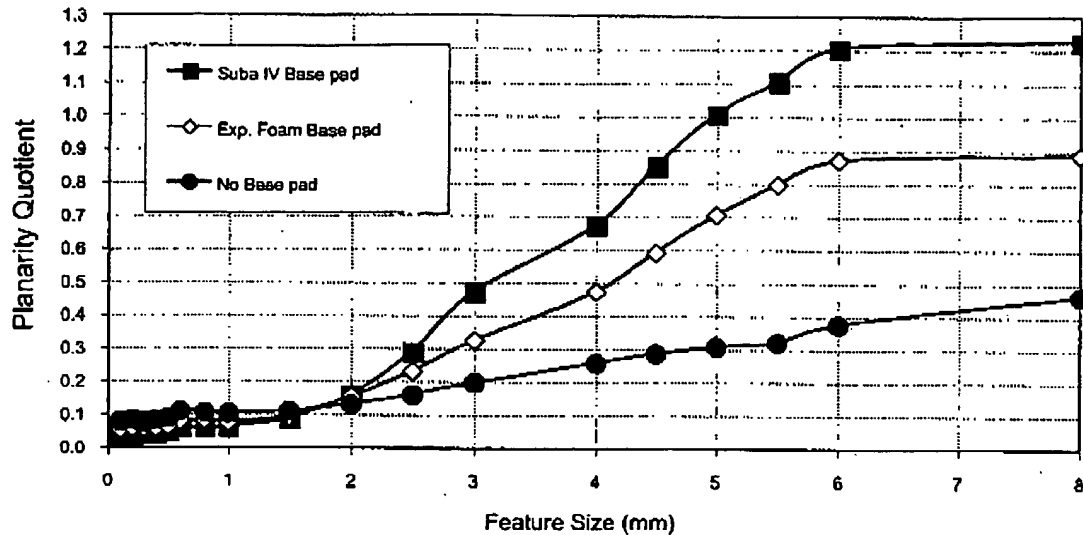| Physical Property	Suba IV^{TM}	Foam Base Pad
Thickness (mm)	1.3–1.4	1.3–1.5
Density (g/cm^3)	0.27–0.32	0.43–0.53
Hardness (Shore O)	65–75	45–55
Compressibility (%)	6–10	2–6
Rebound (%)	90–95	>90

Fig. 6.19. Effect of Base Pad on Planarity

wafer flatness and thickness, as well as physical limitations of the top pad and polishing tool. Using a base pad compromises planarity but improves uniformity across the wafer by reducing the impact of the other problems. The experimental foam base pad has lower compressibility than Suba IV^{TM} which increases the ability to planarize. Thus at a given planarization quotient, the planarization distance of the foam base pad is longer than that of Suba IV^{TM}.

The base pad also has an impact on polishing non-uniformity at the edge of the wafer. As mentioned previously, polishing non-uniformity at the wafer edge depends on both the stiffness of the top pad and also on the compressibility of the base pad. The so-called "edge effects" result in less material being removed near the wafer edge. The problem becomes worse as the stiffness of the top pad increases and the compressibility of the base pad increases [22]. In order to achieve good planarization behavior with minimal edge effects, the preferred pad structure will comprise a stiff top pad over a base pad with just sufficient compressibility to eliminate polishing tool imperfections.

6.7 Relationships Between Pad Properties and Polishing Performance

The relationships between pad properties and polishing performance are complex and not fully understood. One reason for the complexity is that polishing performance is not categorized by a single parameter but by several parameters which are dependent on the scale of the features being polished. Table 6.14 categorizes polishing into three levels – wafer-, die- and feature-scale.

Wafer-scale refers to polishing across the whole wafer surface. Currently

198   David B. James

Table 6.14. Characterization of Polishing Performance Parameters

Polishing Performance Scale		
Wafer-Scale	Die-Scale	Feature-Scale
Removal Rate (RR)	Planarization (P)	Conductor Dishing (CD)
Non-Uniformity (NU)	Defectivity (D)	Oxide Loss (O)
Edge Effects (EE)		Selectivity
Macro-scratches (MS)		Defectivity (D)
Pad Life (L)		Roughness (Rg)

gradually transition to 300 mm. Die-scale polishing applies to polishing across the area of a die, many of which populate the surface of a wafer. The third level, designated feature-scale, refers to the polishing of conductor lines, bond pads, posts and other features within the die. Such features have dimensions measured in sub-microns and microns. For each scale level, Table 6.14 shows the polishing parameters which are most important for that level. In most cases, the meaning of each of these parameters is self-evident and further definition will not be provided here. The reader is referred to other sections of this book for more details.

A second factor complicating an understanding of the relationships between pad properties and polishing performance is the strong dependence of one pad physical property on another. For example, it has been discussed previously that pad density strongly correlates with other properties such as hardness and modulus. Thus, it is very difficult to isolate one property and look at its effect on polishing performance without simultaneously changing other pad properties.

Thirdly, polishing performance depends on many factors other than just the pad. These include polishing tool set-up (e.g. platen and carrier speeds, down-force, back-pressure, carrier head design and carrier film, etc.), slurry-related variables (e.g. abrasive type and loading, pH, flow-rate, etc.), and pad conditioning (e.g. diamond density, exposure and placement, sweep profile, and down-force, etc.). How the pad conditions and the resultant topography of the pad conditioned surface also depends on the properties of the pad itself, as well as the design of the conditioner. In determining relationships between pad properties and performance, the other polishing variables must be kept constant, since many of these have a major impact on polishing results, which in some cases may be greater than the contribution from the pad itself.

Given the above caveats, this section attempts to relate the polishing performance characteristics described in Table 6.14 with specific pad properties. Only the major relationships will be discussed, as summarized in Table 6.15.

Table 6.15. Relationship between Pad Properties and Polishing Performance

Pad Property	Polishing Scale			Conditionability
	Wafer	Die	Feature	
Density (Porosity)	RR, NU	D	CD, O	Yes
Hardness	MS	D	D, Rg, CD, O	Yes
Tensile Properties	L			Yes
Abrasion Resistance	L			Yes
Modulus (Stiffness)	EE, NU	P		Yes
Thickness	L			
Top Pad Compressibility		P	CD	
Base Pad Compressibility	EE, NU	P		
Pad Texture (Grooves)	L, RR, NU, EE			
Pad Roughness	RR, NU	P	CD, O	Yes
Hydrophilicity	RR			Yes

6.7.1 Removal Rate

The rate of removal of the material being polished depends on many factors including both the macro and microtexture of the pad, and also the pad physical properties. Macrotexture is achieved by either punching perforations through the pad or by forming grooves into the pad surface. The latter has been extensively discussed in an earlier section of this chapter. A key role of macrotexture is to prevent hydroplaning of the wafer across the pad surface, arising from an excessively thick layer of polishing fluid under the leading edge of the wafer which limits intimate contact between pad and wafer and significantly reduces removal rate. Levert et al. [26] have studied the thickness of the slurry film for different pad types and shown that hydroplaning is potentially more of a problem with impermeable (Type 4) and semi-permeable (Type 3) pads, rather than with permeable pads (Types 1 and 2). Thus macrotexture becomes more critical for Type 3 and is an absolute necessity for Type 4 pads. Indeed, it has been shown that lack of macrotexture with Type 4 pads results in no removal [15]. It has also been reported [27] for

200   David B. James

than perforations. The reason was attributed to grooves in the polishing pad surface facilitating slurry flow to the wafer surface during polishing. Grooves also enable slurry to be squeezed back out from the leading edge of the wafer, thus eliminating the potential for hydroplaning.

Removal rate also depends on pad microtexture which may be loosely defined as the localized roughness of the pad surface. Microtexture comes from both pad conditioning and from porosity within the pad. Thus other factors being held constant, Type 4 pads which have no inherent porosity give lower removal rates than Type 3 pads [18, 28].

Pad conditioning has a strong effect on removal rate and removal rate stability and has been studied extensively [13, 28, 29, 30, 31, 32, 33]. As discussed in the first chapter, it is known that either *in-situ* or *ex-situ* conditioning of the pad surface is required to achieve and maintain stable removal rates. The role of conditioning is to create asperities on the pad surface which contact the wafer. Without conditioning, the asperity population decays during polishing and removal rates rapidly decline. The rate of decline is usually higher for Type 4 than Type 3 pads, since in Type 4 pads there are no inherent asperities from a pore structure, such as that found in Type 3 pads.

Cook [13] and Hetherington [32] have independently used scanning electron microscopy to study changes in the surface of IC2000™ (Type 4) and IC1400™ (Type 3) pads respectively during polishing in the absence of conditioning. For both pad types, the photomicrographs clearly showed a progressive decrease in pad asperities and the increasing formation of a smooth mesa-type structure. Hetherington postulated that the asperities were deforming under the shearing conditions associated with polishing, whereas Cook favored a progressive abrasive smoothing of the asperities. It is probable that given the conditions of polishing both shear deformation and abrasive loss are occurring.

Bajaj et al. [28] and Oliver et al. [33] have also studied the relationship between pad properties and removal rate decline in the absence of conditioning. During polishing, pad surface roughness decreases because the shearing forces of polishing reduce the height and number of pad asperities. The rate at which the asperity population declines was shown to be inversely proportional to the shear modulus of the bulk polymer.

6.7.2 Non-Uniformity

Removal rate uniformity across the wafer surface (within wafer non-uniformity) also depends on the macro and microtexture of the surface of the polishing pad in contact with the wafer. However, as previously discussed, because of edge effects non-uniformity also depends on the base pad and the balance of properties between top pad stiffness and base pad compressibility [22].

Goetz [34] has studied the effect of the base pad construction on pla-

single-layer and two-layer sub-pad constructions were analyzed. As expected, the effect of sub-pad construction was greatest in the multi-millimeter length scales (die to wafer scale) and attenuated by the stiffness of the upper polishing layer. Single and two-layer sub-pads responded in different ways to loading, such that the response of the single-layer sub-pad was dominated by contact mechanics, while the two-layer sub-pad response was dominated by plate bending.

Polishing non-uniformity across the wafer is also strongly dependent on the polisher design, especially the carrier head. Base pads were originally used to overcome limitations with the polishing tool. As polisher designs become more sophisticated, the need for base pads will decrease and polishing uniformity across the wafer surface, including the edge exclusion region, will improve. This trend will be especially important as the industry transitions to larger diameter wafers.

6.7.3 Pad Life

Pad life is a complex issue since several factors can determine the useful life of a pad. Also, different manufacturers have different criteria for determining pad life. However, it is usually determined by the point at which some specific polishing parameter exceeds the control limit for that parameter. Such parameters can be removal rate, non-uniformity or, for shallow trench polishing, selectivity of oxide to nitride. Two events which commonly limit pad life are glazing of the pad surface and loss of macrotexture. Glazing is the build-up of polishing debris on the pad surface which clogs the pores [28, 33, 35, 36] and becomes increasingly difficult to remove by further conditioning. This problem is often seen, especially with Type 1 and 3 pads. The second event involving loss of macrotexture results from the abrasive wear of the pad during polishing, especially from the pad conditioning process, which reduces the overall pad thickness and the depth of the grooves in the pad surface. Once the grooves have been abraded, hydroplaning will occur for the reasons discussed above. Secondly, as the thickness of the top pad decreases during polishing, the pad will become less stiff and polishing planarity will decrease. Pad life may be increased by cutting deeper grooves [15, 25] and by increasing pad thickness so that pad stiffness is not compromised.

6.7.4 Planarity

At the die-level, achieving planarity of the features is an important concern and a main driving force for CMP polishing as a device fabrication step. It has been recognized for sometime [37, 38, 39, 40, 41] that stiffer and harder pads give improved planarity. As has been discussed previously, for Type 3 pads stiffness and hardness are often strongly correlated to one another

202   David B. James

However, it is becoming generally accepted that stiffness of the polishing pad is the more important property determining planarity. As discussed earlier, pad stiffness depends on both the pad modulus and thickness.

Experimentally, the relationship between planarity and pad stiffness has been independently verified by several researchers [42, 43, 44]. For example in an oxide CMP process, the planarization performance of a Type 3 pad (IC1000™) was compared to that of a Type 4 pad (IC2000™). With other polishing parameters kept constant, the polishing data clearly demonstrated that the stiffer IC2000™ pad produced improved planarity. Other work [41, 44], and data presented earlier in this chapter, have shown that increasing the pad thickness produces a similar response and that less compressible or thinner base pads also improve planarity.

Simplistically, the improved planarity achieved by using stiffer pads comes from the reduced bowing of the pad as it planarizes. This phenomenon has been modeled by several groups [41, 44, 45], basically by treating the polishing pad as a beam in deflection. Nanz and Camilletti [46] have summarized the various modeling approaches and critiqued the strengths and weaknesses of each model. Steigerwald et al. [7] have also reviewed models describing planarity.

Grillaert et al. [41] have analyzed oxide thickness variation after CMP within a die (WIDNU) for two extreme cases: perfect pad bending and no pad bending. The perfect pad bending model consisted of a thin top pad on a soft bottom pad. In this case, the top pad bends easily and large oxide variation was found. The no pad bending case, consisting of a thick inflexible top pad, significantly reduced oxide thickness variation. Experimentation confirmed that WIDNU for a real stack pad always falls between these two extreme cases.

There is also growing evidence that pad roughness has an effect on planarity. Cook et al. [47], in attempting to analyze the physics, mechanics and chemistry of the CMP process, have concluded that the best descriptor of that process is an asperity contact model. The authors found that pad roughness influences the limits to achievable planarity, such that planarity was degraded as pad roughness increased.

Renteln and Coniff [48] have related pad roughness back to pad modulus by hypothesizing that roughness created on the surface of the pad can be treated like an additional elastic layer. This can be modeled as a two-layer composite structure where the overall modulus depends on the volume fractions (thicknesses) and moduli of the individual layers. Since the surface layer will have a more open pore structure than the bulk, it is reasonable to assume that its modulus will be lower than that of the underlying layer. Using this model, Renteln and Coniff were able to explain the experimental data. In the same paper, they also postulated that planarization rate depends solely on the elastic modulus characteristics of the pad and that anelastic effects of the

Using a different approach to explain the dependence of planarity on pad roughness, Yu et al. [49] have developed a statistical asperity model which relates the time-dependent deformation of asperities to the planarization of device features. The model assumes that the applied load is distributed between the asperities and the fluid film which fills the gap between the polishing pad and the wafer. At low platen speeds the hydrodynamic pressure of the fluid film is small and the load is principally carried by the asperities. The model also relates asperity size to trench widths. For wide trenches where the trench is larger than the asperity, the asperity can contact and remove material from the trench bottom. However, for narrower trenches, device geometry restricts asperity contact and polishing is selective. For wide trenches, geometry effects become insignificant and polish selectivity disappears. In order to match better the model predictions with experimental data, the authors proposed that, since the pad material is viscoelastic, an asperity does not deform instantaneously as it enters or leaves a trench. In consequence, contact to the trench bottom is reduced and polish selectivity is increased.

Grillaert et al. [50] have developed a model which attempts to explain why step height as a function of polishing time initially decreases linearly followed by an exponentially decreasing reduction as planarity is achieved. Also, their model predicts the influence of pattern dependence on step height reduction. The model assumes that the applied load is only supported by the features in contact with the pad, the pad has limited compressibility, the pad bends perfectly, Preston's equation [51] can be extended to local removal rates and pressures, and that the pad is perfectly smooth. Since the pad has limited compressibility, during initial polishing the entire load is supported by the up features only and removal rate of these features is high. As long as the step height is high enough the pad does not touch the down features and no material is removed there. As polishing proceeds step height reduces. At some point, the step height is small enough so that the pad comes into contact with the down features. When this occurs the pressure will be distributed over both up and down features and the rate of further step height reduction will decrease. Since the pad surface is not perfectly smooth but is comprised of asperities, the protruding asperities can remove material from the down features before the average pad surface is in contact with the down features.

From the above discussion, the three pad properties determining planarity are pad stiffness, pad compressibility and surface roughness from pad asperities. Also the time dependence of these properties is important and must be considered. It is also probable that the relative importance of each depends on the material being polished. To date, no published model satisfactorily combines these into a single, working, predictive model.

6.7.5 Macro-scratches and Defectivity

204   David B. James

and micro-scratches, and other defects involving physical damage of the device being polished. In general, to avoid scratches, softer materials such as aluminum [52] or copper are polished with softer pads, and harder materials like oxide and tungsten use harder pads. However, there are many exceptions to this rule. For example, very soft Politex™ pads are used to polish tungsten plugs. One reason to use harder pads to polish softer materials is the need for good planarity and, as previously discussed, higher hardness and stiffness are often linked.

Defectivity also appears to be related to pad porosity. One explanation is that pores in the pad surface become clogged with polishing debris which can cause scratching and leave residual particles on the wafer surface. For copper CMP, it has been shown that an experimental unfilled Type 4 pad gave a significantly lower level of defects after polishing than a standard Type 3 IC1010™ pad [21].

6.7.6 Conductor Dishing and Oxide Erosion

Conductor dishing and oxide erosion are feature-level polishing parameters applicable to metal CMP and are especially important for next generation devices using copper metallization. As feature sizes decrease and conductors become smaller, copper is emerging as the preferred metallization because of its superior electrical conductivity over aluminum and tungsten. Copper damascene processes are being developed as the preferred method of manufacturing [53]. In these processes, trenches are created in the oxide dielectric layer. Copper is then deposited by electroplating, filling these trenches and covering the surface of the rest of the chip. CMP polishing is used to polish away the excess copper, leaving only the inlaid interconnect lines.

The objective of the copper polishing step is to achieve planarity of features with only minimal loss in the cross-sectional area of the conductor lines, so that high conductance is maintained. However during polishing, conductor dishing and oxide erosion occur which produce device feature deviations from the idealized damascene structures. Conductor dishing is defined as the difference in elevation of the insulator region to the metal line and oxide erosion is the loss of dielectric within the conductor feature array. Additional oxide loss, known as field oxide loss, occurs globally because the oxide polish rate is non-zero during over-polishing. Total conductor thickness loss which must be minimized is the sum of field oxide loss, local oxide erosion and conductor dishing. Figure 6.20 further illustrates the terms dishing (D), oxide erosion (E) and field oxide loss (F).

Several authors [53, 54, 55, 56, 57, 58] have independently developed models to explain the phenomenon of dishing. In general, their models are extensions of those used for within die planarity as discussed earlier, and take into account pad properties such as pad stiffness, pad compressibility, hardness
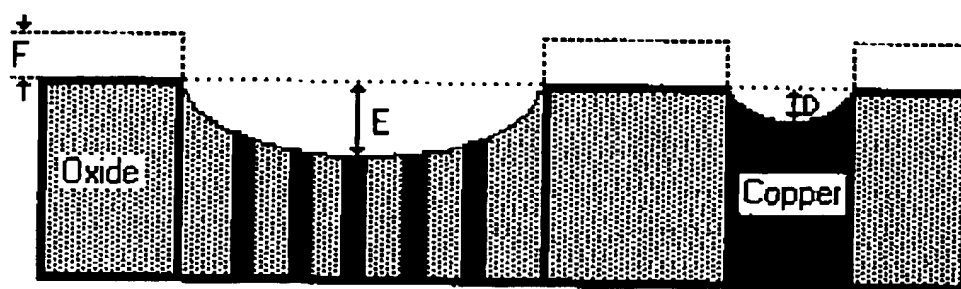
Fig. 6.20. Schematic Illustration of Dishing, Oxide Erosion and Field Loss

In an early paper on dishing of copper damascene structures, Steigerwald et al. [53] extended the pad deflection beam model of Sivaram et al. [59] to include the effects of both pad compressibility and roughness. Pad compression was taken into account by assuming that only the surface layer of the pad compresses as it pushes against the wafer and, as the pad rides over a recess, that some of the compression is relieved. The assumption was made that if pad deflection is due to pad compression, then only the near-surface layer is assumed to bend. Pad roughness was incorporated into the model using the concept of Renteln and Coniff [60], in which the rough surface layer is assumed to have a lower elastic modulus than the bulk material. In agreement with experimental observations, the model predicts that stiffer, smoother pads of low compressibility will give lower dishing.

In a more recent paper, Yang [57] has attempted to develop a quantitative model of dishing based on a Prestonian analysis of different removal rates for high and low copper features. The model incorporates terms for pad bending and pad compressibility. Calculated results of dishing are in good agreement with experimental data, such that the model accurately predicts copper dishing as a function of line-width and over-polish. The model further predicts an increase in copper dishing as feature size increases due to pad bowing. The wider the metal feature or the more compliant the pad, the more the pad can deform to remove metal within the dish. Thus the model predicts that both low pad compressibility and low conformity are desirable for reducing copper dishing.

Nguyen et al. [58] have developed an alternative model to explain dishing based on the assumption that material removal occurs predominantly at the pad/wafer contacts. Their statistical contact mechanics model assumes: a) material removal occurs at the mechanical contact between pad asperities and wafer, b) distribution of pad asperity contact size is Gaussian, c) different removal rates occur for asperities with contact size smaller and larger than the line width, d) Preston's law is valid, e) dishing occurs during over-polishing, and f) oxide erosion is neglected. Excellent agreement is obtained between experimental data and model predictions for both time dependence and feature size dependence of dishing. Their model predicts that pad surface

206   David B. James

hence on dishing. This intuitively makes sense given that the typical roughness of a pad surface is comparable to the size of the conductor features being polished. Also it predicts the importance of pad conditioning in producing an optimized surface topography for polishing.

Closely related to dishing is the phenomenon of oxide erosion. This is a thinning of the oxide layer resulting from a non-zero oxide polish rate during the over-polish step. Like dishing, it causes a reduction in conductor cross-section and is equally undesirable. As discussed above, less compressible and stiffer pads are preferred to minimize dishing. However, such pads also tend to be harder which can lead to increased oxide erosion, since harder pads tend to have higher oxide polish rates [53]. Thus from a pad perspective, there are opposing needs in terms of pad hardness. One solution to the problem is to use a fairly hard pad in combination with a slurry which has a much higher removal rate for copper than oxide. Such slurries are discussed in detail elsewhere in this text.

Yang [57] has extended his quantitative model of dishing to describe oxide erosion. The model accurately predicts oxide erosion as a function of pattern density and over-polish time.

6.7.7 Pad Conditioning

As mentioned already several times in this chapter, pad conditioning has a major impact on all aspects of polishing performance. Many pad properties affect and are influenced by pad conditioning. As an example of the former, it is found that pads containing porosity (Type 3) are more readily conditioned than Type 4 pads. This is because porosity reduces the abrasion resistance of the pad which facilitates the creation of microtexture by the diamond conditioner. The mechanism of microtexture creation is also affected by the tensile, hardness and modulus properties of the pad. For pads which have high modulus and hardness with low ductility, the conditioning disk diamonds cut channels by preferentially fracturing and removing pad material. In contrast, for softer, lower modulus and more ductile pads, the diamonds cause plastic flow and plough the material aside rather than by physically abrading it to create channels. So in the former cause, pad conditioning results in higher pad wear, whereas in the latter case pad loss during polishing is significantly less, since the surface is essentially being rearranged. This is especially true when polishing softer materials such as copper which do not themselves significantly wear the pad surface.

Examples of pad properties which are affected by conditioning are, of course, pad roughness but also pad hydrophilicity. The process of roughening the pad surface by conditioning in the presence of either water or polishing fluid increases the critical surface tension of the pad and makes it more hydrophilic. This aids the wetting of the pad surface by the polishing fluid and

6.8 Slurryless Pad Technology

Although "Slurryless Technology" is covered in a separate chapter in this book, for completion given its emerging importance, it is appropriate to include a brief discussion of Slurryless Pad Technology in this chapter.

Conventionally, CMP polishing is accomplished by using an abrasive particle-containing slurry in combination with a polishing pad. While such slurries are universally employed, it is recognized that their use gives rise to significant problems:

1. Although polishing is practiced in a clean room environment, the particles themselves are a serious source of contamination when polishing semiconductor devices and can leave residual particles on the polished wafer surface.

2. The quality of the surface produced during polishing is highly dependent upon the particle size distribution and composition of the particles in the slurry. Anomalously large particles, even in extremely small concentrations, are commonly responsible for scratches and other post-polish mechanical defects. These are highly deleterious to the yield of semiconductor devices processed by polishing. At the solids content of these polishing slurries (typically >12%) it is practically impossible to use filtration to remove the oversize particles due to clogging effects on the filter medium. Thus expensive and time consuming efforts have been made to control and reduce oversize particles in the slurries employed. However, there are few practical safeguards against their accidental introduction.

3. A desirable practice in CMP polishing is to reuse or recirculate the polishing slurry to reduce manufacturing cost and the quantity of waste products from the operation. However, the activity of polishing slurries is commonly observed to vary with time when recirculated. This may be due to the addition of dross, or polishing byproducts from the substrate into the slurry solution, attrition or breakdown of the polishing particles themselves during use, or chemical changes in the particles which reduce activity. This level of variation in recirculated slurries is unacceptably high for processing semiconductor devices. Recirculation of this system is exceedingly difficult because the byproducts of the polishing process are often practically indistinguishable from the original slurry particles, and it is equally impossible to control their size or remove them from the solution. In consequence, the solid particle content of the recirculated slurry continuously increases with time. As the polishing rate is directly proportional to the solids content of the slurry, practical control of the polishing rate is difficult. A serious additional problem is the accidental incorporation of oversize contaminant particles into the recirculating slurry, often due to substrate breakage. The aforementioned difficulties in filtering slurries make it virtually impossible to remove these contam-

208   David B. James

Because of the above concerns, recirculation of slurry is not widely practiced in the polishing of most semiconductor devices because of the need to control activity precisely and the avoidance of damage by contaminants. Slurry is usually simply used once and disposed of as waste. As a result, the cost of slurry and slurry waste disposal is the single largest contributor to the cost of polishing semiconductor devices.

From the above, it is clear that a polishing process which uses a particle-free liquid which can be readily recirculated and kept in a constant particulate-free state, would be preferred in the processing of semiconductor wafers over conventional particle-containing slurries. Such particle-free liquids, commonly known as "Reactive Liquids" are beginning to find acceptance for CMP polishing [65, 66, 67]. Typically, reactive liquids are based on similar chemistries to those of conventional particle-containing slurries and are used in combination with polishing pads which themselves contain abrasive particles incorporated into the pad matrix.

Table 6.16 shows recent patents describing reactive liquid chemistries and types of slurryless pads. The reader is referred to these patents and the "Slurryless Technology" chapter of this book for a more detailed discussion of polishing using slurryless technology.

6.9 Future Trends in Polishing Pads

For the foreseeable future, CMP polishing will remain as an integral manufacturing operation in the production of semiconductor devices. As CMP polishing evolves and semiconductor devices become more complex with finer feature geometries and more metallization layers, the need for more reproducible, precision polishing performance will increase. This will necessitate improved polishing pads with less "pad to pad" variability which provide more predictable and consistent polishing performance. CMP will become more of a standard process and semiconductor manufacturers will continue to expect reduced cost of ownership for polishing consumables. This will initially impact the more established CMP polishing operations, such as oxide and tungsten polishing, but will eventually also impact still emerging processes, such as copper CMP.

With respect to polishing pads, it is expected that polyurethanes will remain as the preferred polymer type because of their attractive combination of properties, their versatile chemistry, the ability to control pad properties over wide ranges, and the ability to form pads by a wide range of manufacturing processes. Pad suppliers will continue to develop alternative, simpler pad manufacturing processes with the goals of more consistent pad properties at reduced cost.

Work will continue by pad suppliers, semiconductor manufacturers, and academics to develop a more comprehensive understanding of the relation

Table 6.16. Patents describing Reactive Liquids and Slurryless Pads

Patent #	Assignee	Brief Description of Invention
US4,393,628, US4,466,218, US4,613,345	IBM	Slurryless pads for disk polishing, comprising a polyurethane foam containing fixed alumina abrasive
US5,152,917, US5,304,223, US5,435,816, US5,454,844, US5,549,961, US5,692,950, US5,958,794, US6,007,407	Minnesota Mining and Manufacturing Company	Extension of 3M's Microreplication technology. Photopolymerizable slurryless pads comprising a three-dimensional fixed-abrasive element
US5,725,417, US5,782,675	Micron	Conditioning and refurbishment of fixed-abrasive pads
US5,759,918	Obsidian	Linear polishing tool for fixed-abrasive pads
US5,932,486, US6,030,899	Rodel	Slurryless polishing using reactive liquids free from particulate matter in combination with polishing pads having a multiplicity of surface nanoasperities.
US6,022,264, US6,099,394, US6,069,080	Rodel	Slurryless polishing pads comprising a high modulus phase and a low modulus phase
WO99/55493	Ebara	Grinding wheel for slurryless polishing comprising abrasive grains and pores in a polymeric binder
EP 0 874 390 A1	Hitachi	Grindstone for slurryless polishing comprising abrasive grains and a bonding resin
US6,117,775	Hitachi	An abrasive-free reactive liquid for polishing metal films comprising an oxidizer and a substance which renders oxides water-soluble

necessity encompass all aspects of the polishing process, including interactions of the pad with the polishing fluid, the role of conditioning and polishing parameters, and of polishing tool design. From such work, it is expected that polishing consumable suppliers will be able to offer manufacturers a total

210   David B. James

tioner combination. Such combinations will enable synergistic performance advantages for the customer.

Industry trends that are currently in their infancy which will impact pad suppliers are the shift to 300 mm. wafers, polishing with abrasive-free reactive liquids, the increasing use of copper metallization in combination with low K dielectrics, and the growing importance of linear polishing tools. All four are driven by the need to reduce semiconductor device manufacturing costs, improve yields and performance, and to increase throughput. These issues are separately discussed in detail elsewhere in this book. The important point to note is that the pad can no longer be developed in isolation from the rest of the polishing system but must be developed and optimized with respect to the polishing tool, the type of wafers being polished, and the polishing fluid.

6.10 Acknowledgements

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212   David B. James

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